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NIF Laser Line Replaceable Units (LRUs)

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ABSTRACT

The National Ignition Facility (NIF) is designed with its high value optical systems in cassettes called Line Replaceable Units (LRUs). Virtually all of the NIF's active components are assembled in one of the ~4000 electrical and optical LRUs that serve between two and eight of NIF's 192 laser beam lines. Many of these LRUs are optomechanical assemblies that are roughly the size of a telephone booth. The primary design challenges for this hardware include meeting stringent mechanical precision, stability and cleanliness requirements. Pre-production units of each LRU type have been fielded on the first bundle of NIF and used to demonstrate that NIF meets its performance objectives. This presentation provides an overview of the NIF LRUs, their design and production plans for building out the remaining NIF bundles.

Keywords: Fusion, High Energy Lasers, Laser Fusion, Solid State Lasers

INTRODUCTION

The National Ignition Facility (NIF) is the world's largest laser system. It is comprised of 192 individual laser beams that are 40 x40 cm and each produce up to about 20,000 joules of 1.06 micron laser light in a several nanosecond pulse. The NIF's 192 beamlines are arranged into eight-beam groups called bundles. Each bundle is independently enclosed throughout the entire path to the target chamber where all the beams are focused onto a target (Figure 1). The enclosures and the structure that support the laser hardware (without optics) are called the beam path. The laser system is completed by installing Line Replaceable Units (LRUs) with optics into the beam path.

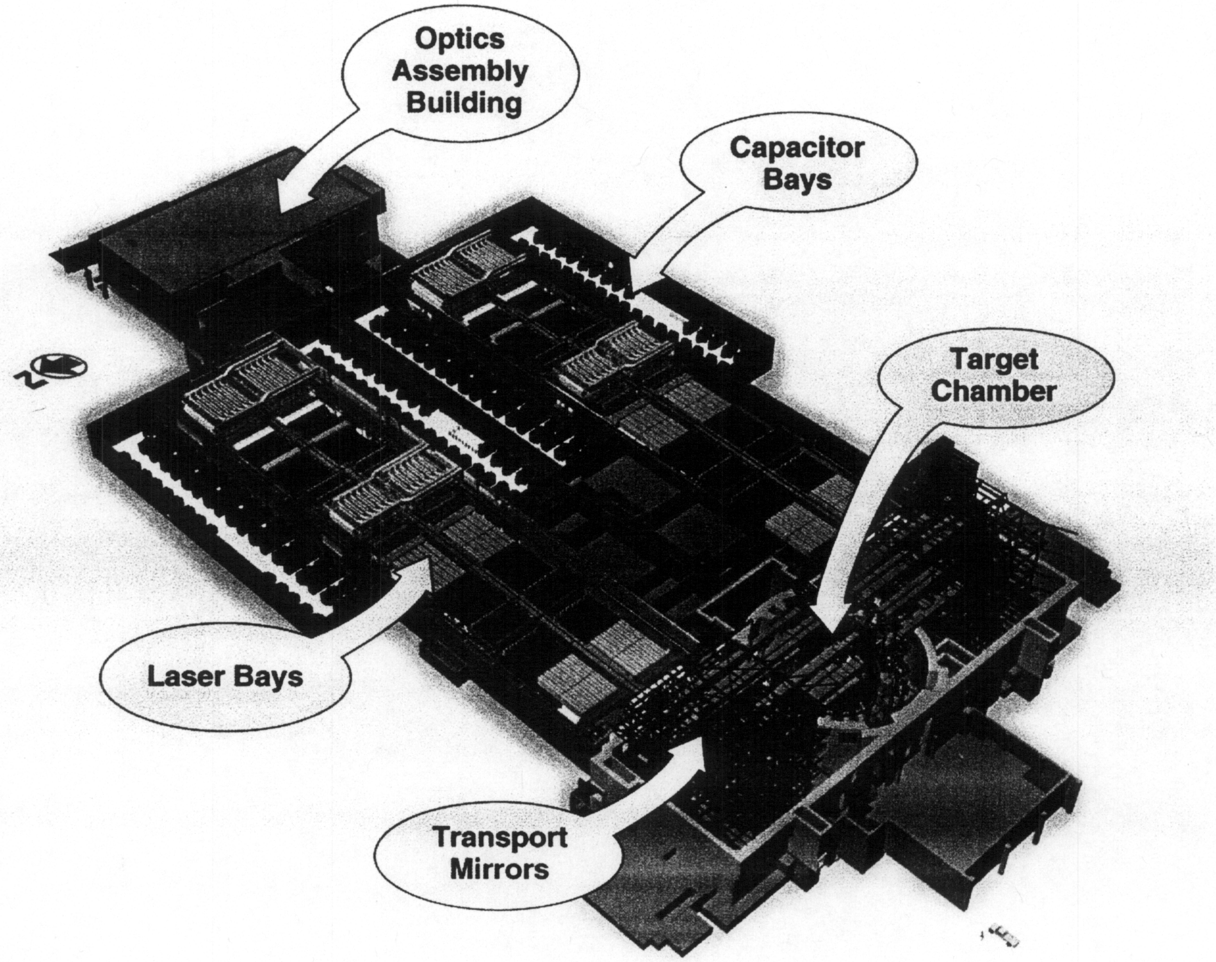

Figure 1. CAD model of the NIF with the roof removed to reveal the beam path infrastructure in the laser bays, switchyards and target area. The attached LRU assembly facility is a clean room where optics are installed in their mounts.

Figure 2 shows the architecture of the laser system including the key optical components that comprise a single beam line. Each of NIF's 24 bundles contains over 30 types of optomechanical LRUs including mirrors, lenses, laser amplifier slabs, diagnostics and alignment sensors. The completed NIF will include over 4200 LRUs in all.

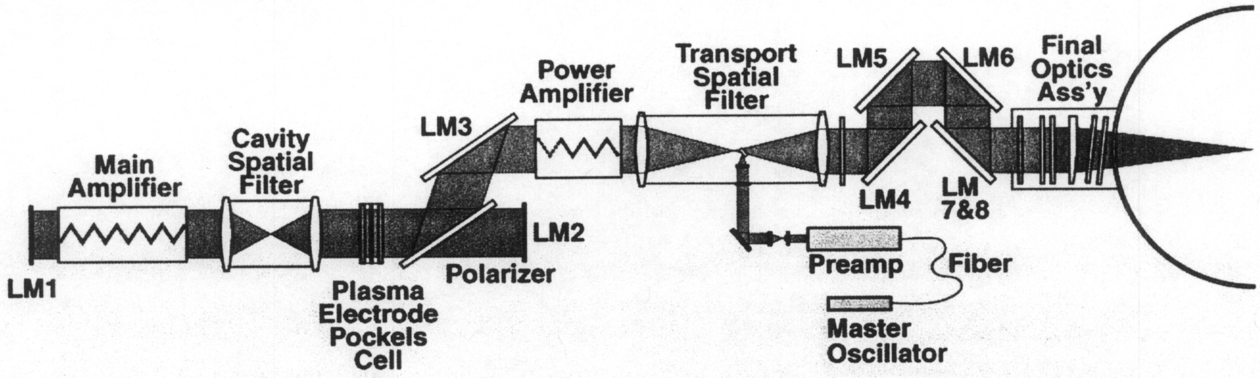

Figure 2. Optical schematic of the NIF main laser.

Each LRU must meet many requirements derived from the overall performance requirements of the laser. A primary design challenge for all of the optical LRUs is to meet demanding requirements on mechanical precision, stability and cleanliness. The precision of the optomechanical assemblies is driven by a design philosophy of eliminating adjustment points in the system. Thus the LRU assemblies, some the size of a phone booth, must be pre-aligned during assembly and then placed on precisely located kinematic mounts in the beam path to position optics to within less than 0.5 mm. The stability requirements are derived from the need to maintain alignment of the (several hundred meter long) optical path on the target for over an hour while the system prepares for a shot. Particles on the optics can result in obscurations, optics damage or both depending on the laser fluence at that location. Therefore, the cleanliness inside the laser enclosure must be less than Class 1 (Fed 209 Class) on average to preserve the pristine condition of the optical surfaces throughout operation of the facility. Each LRU must therefore be installed in the beam path in a way that maintains the hermetic integrity of the beam path enclosure.

This LRU-based design approach represents a departure from that of previous large solid-state lasers, where many of the optomechanical assemblies were integrated with the beam path. In previous systems, removing an optic for inspection or replacement required that a section of the beam path be removed. This would necessitate construction of a local clean room over the area where the beam enclosure was to be removed and added complexity to the design of the beam enclosure. This previous approach could not work for a system the size and complexity of the NIF. LRUs must be replaceable in 2-3 hours so that all the beams remain available for experiments. The NIF LRUs are replaced using portable clean rooms called canisters, with robotic mechanisms that "dock" to the beam path and cleanly transfer the LRU into or out of the laser enclosure. Each LRU has design features that precisely locate the LRU within the canister. Most LRUs are installed through hatches in the bottom of the beam path enclosure (amplifier slabs, flashlamps, Pockels Cells, mirrors, spatial filter lenses). Figure 3 shows the robotic canisters "docked" to the main amplifier while laser amplifier slab and flashlamp LRUs are installed. An important requirement on this hardware is the ability to install or remove an LRU without contaminating the clean beam path. The laser enclosure must remain below Class 100 during the transaction. Airborne particle measurements data taken during installation and removal of an LRU (Figure 4) show that the system performs well within the required cleanliness envelope.

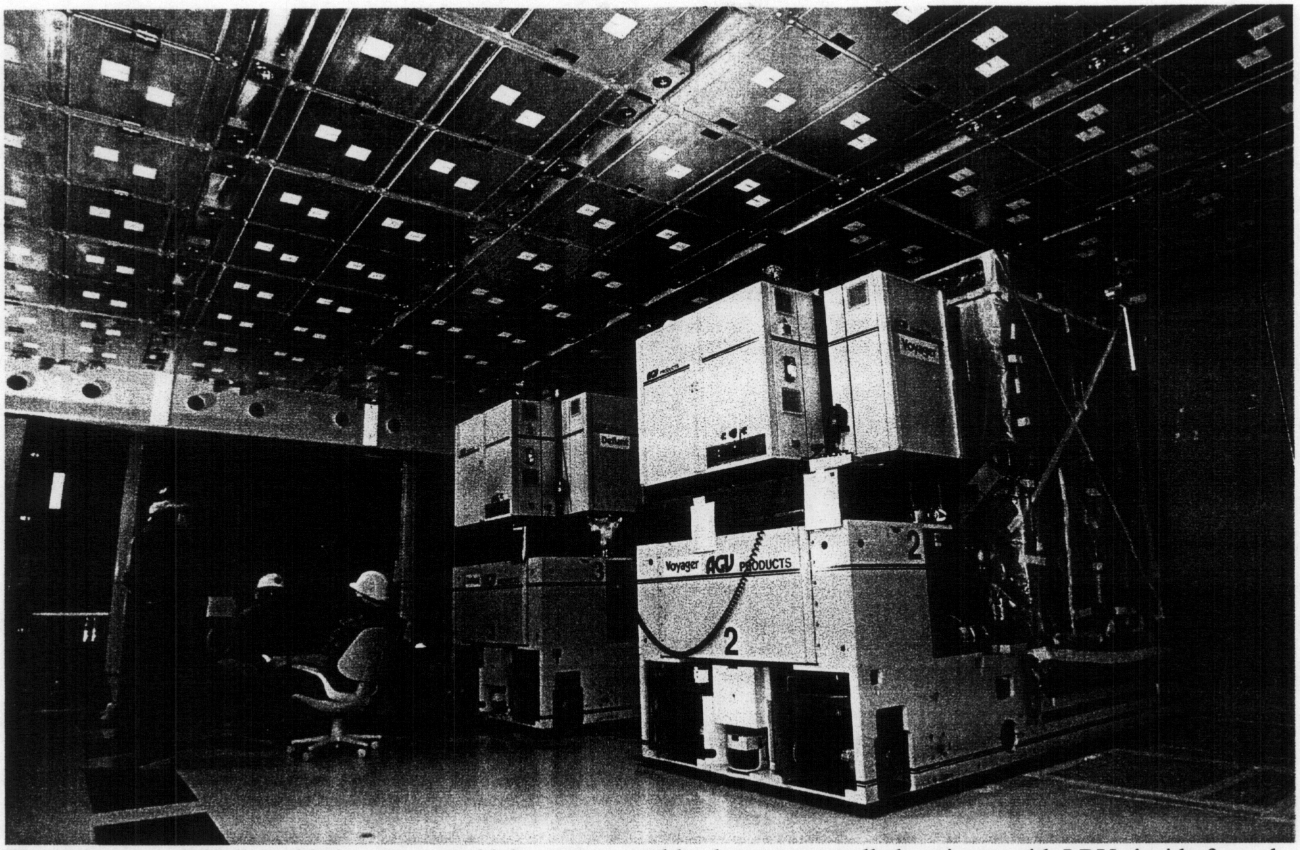

Figure 3. Automatically guided transport vehicles carry portable clean rooms called canisters with LRUs inside from the assembly area to the laser for installation. This picture shows two canisters docked to the beam path enclosure while amplifier slab and flashlamp LRUs are installed.

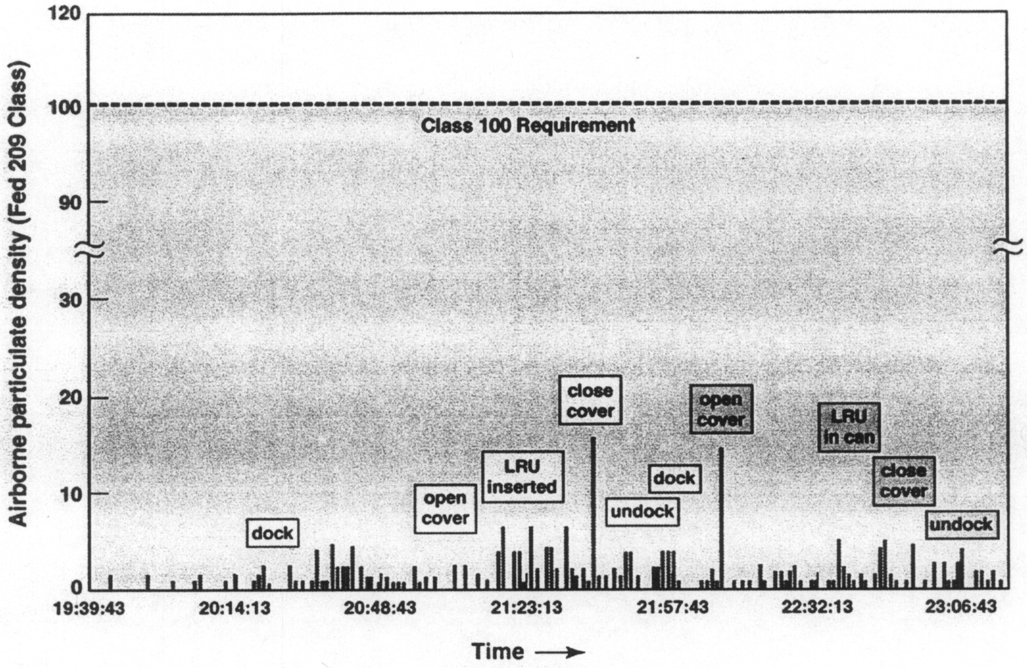

Figure 4. Airborne particle measurements taken during installation and removal show that the canister system performs well within the Class 100 requirement during LRU transactions.

Table 1 lists the major classes of LRUs in the NIF along with their basic characteristics and functions. The following sections provide an overview of the various NIF LRU designs following the path of the laser pulse from the preamplifier to the final optics assembly.

LRU Name	Function	Size (m)	Weight (kg)	# of beams	Quantity
Preamplifier	Amplifies master oscillator pulse from ~ 1 nJ to ~ 6 J	4.5 x 0.7 x 1.1	1,700	4	48
Spatial Filter Lens	Focuses laser beam at center of spatial filter and recollimates	2.2 x 0.5 x 0.7	390	4	192
Spatial Filter Tower	Positions spatial filter pinholes and alignment sensors. Provides means to inject preamp. beam and extract diagnostic beam	2.4 x 0.9 x 1.4	1,100	8	72
Amplifier Slab	Holds Nd:glass laser slabs to amplifier laser	0.7 x 0.5 x	290	4	864

	pulse	2.1			
Amplifier Flashlamp	Provides spatially tailored pump light to amplifier laser slabs	2.6 x 0.7 x 0.1	70	4	1296
Power Conditioning Module	Provides electrical pump pulse to amplifier flashlamps	3.3x 1.5 x 3.4	11,000	8	216
Plasma Electrode Pockels Cell	"Switches" light into and out of the multipass cavity in conjunction with the cavity polarizer	2.5 x 0.9 x 0.6	800	4	48
Deformable Mirror (LM1)	Cavity end mirror corrects wavefront errors in the optical system	2.3 x 0.5 x 0.6	600	4	48
Beam Transport Mirrors	Transport laser beams to Target Area	1.3 x 1.2 x 1.1	60	2 or 4	320
Final Optics Assembly	Frequency converts laser beam from IR to UV, focuses beams to target chamber center			4	48

Table 1. List of LRU types with major characteristics

DESIGN OVERVIEW

1. Preamplifier

The NIF preamplifier (Figure 5) is the most complex LRU in the NIF Laser System. It includes roughly 100 individual optics from 0.5 to 12 cm in diameter. Each of the 48 LRUs amplifies the ~1 nanojoule pulse from the master oscillator system to about 6 joules. An optical splitter outside the preamplifier distributes the energy to four NIF beamlines that comprise the top or bottom half of a bundle. The preamplifiers are assembled, aligned and tested off-line before being installed on precision rails for positioning in the laser. Most of the 10^{10} gain in the preamplifier LRU comes from a diode-pumped regenerative amplifier operating at 1 Hz. The rest comes from a flashlamp pumped rod amplifier that fires about every 20 minutes. In addition to amplifying the pulse, the preamplifier provides a spatial shape and intensity profile that propagates through the laser chain.

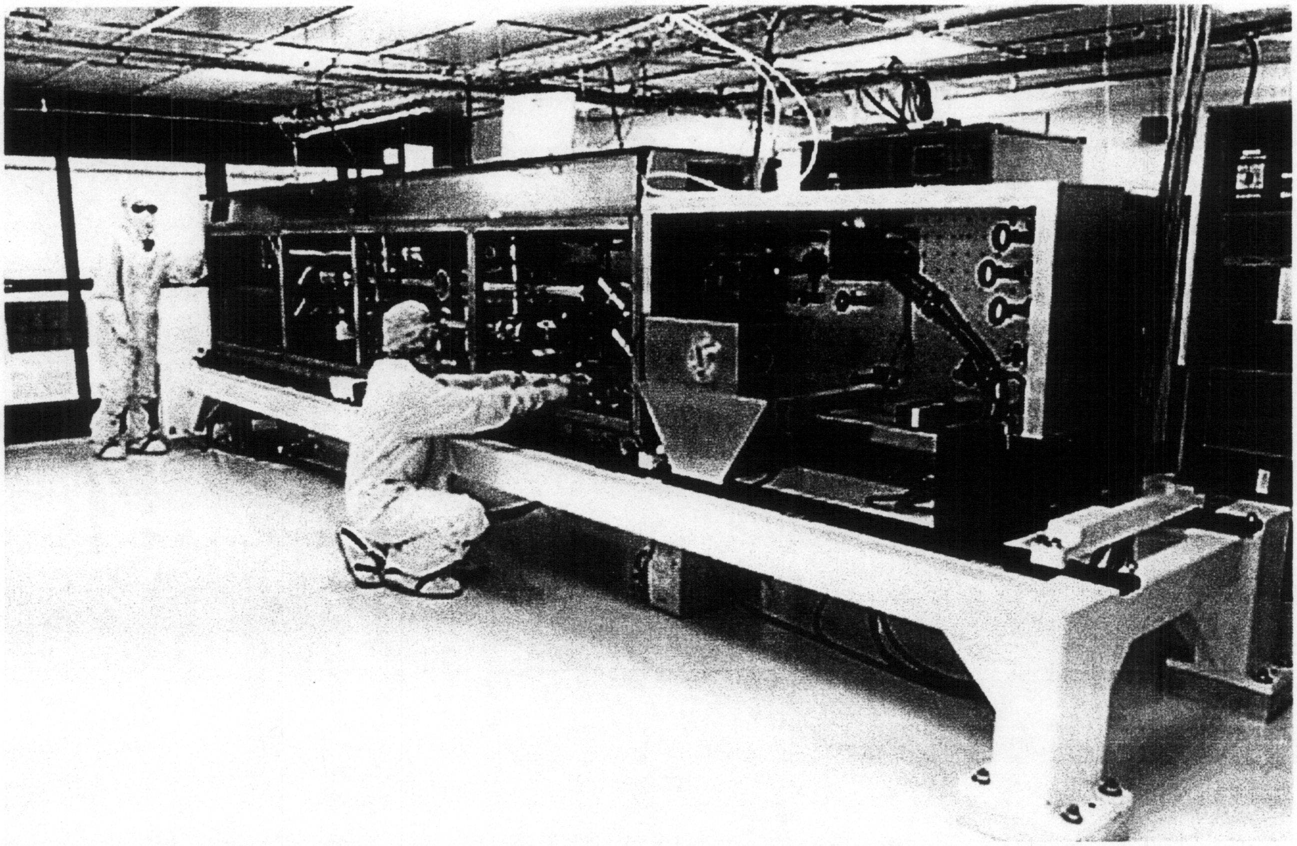

Figure 5. The preamplifier amplifies the seed pulse from the master oscillator by 10 orders of magnitude to ~6 joules. It also puts an intensity profile on the pulse to pre-compensate for gain non-uniformity in the main amplifier. In this picture, the 3.5 meter long preamplifier is undergoing final testing in preparation for installation in the laser bay.

2. Spatial Filters

The output pulse from the preamplifier, after the 1:4 splitter, is injected into the main beamline at the pinhole plane of the Transport Spatial Filter (Figure 2). The beam expands from ~3 cm to the full 40 cm before being recollimated by the Spatial Filter (SF) Lens LRU on its way to the main laser cavity. The SF Lens LRU (Figure 6) forms part of the boundary of the vacuum environment inside the spatial filters. The frame is machined from stainless steel plate, resulting in a very stiff LRU that can be readily cleaned to the stringent NIF requirement for LRU surfaces.

The Spatial Filter Tower LRUs are located at the center of each of NIF's two spatial filters. These are the largest LRUs in the system and perform several functions including insertion of the low energy beams from the preamplifier, spatial filtering of the main laser beams, pathway for light to get to laser diagnostics and providing reference beams to align the optical system. The Tower LRUs are constructed by installing modular optical systems called platforms onto a rigid frame that spans a bundle of NIF. The platforms are assembled and tested by a vendor and then integrated into the LRU frame in the NIF Optics Assembly Building (OAB) clean room (Figure 7).

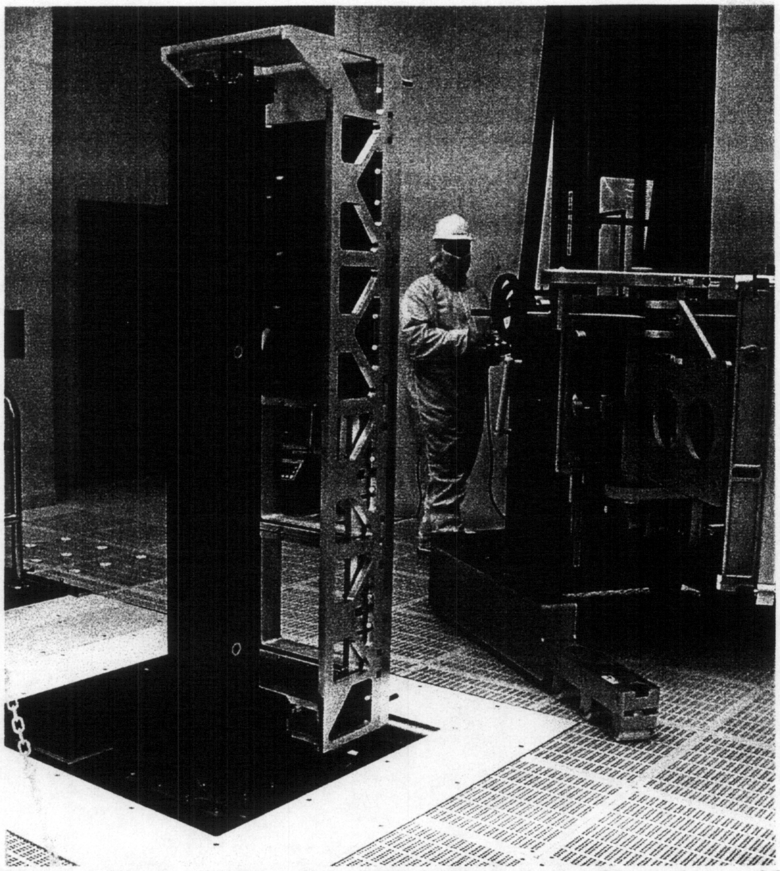

Figure 6. The Spatial Filter Lens LRU holds the lenses for a column of four beams within a bundle. This LRU forms part of the vacuum barrier for the spatial filter enclosure.

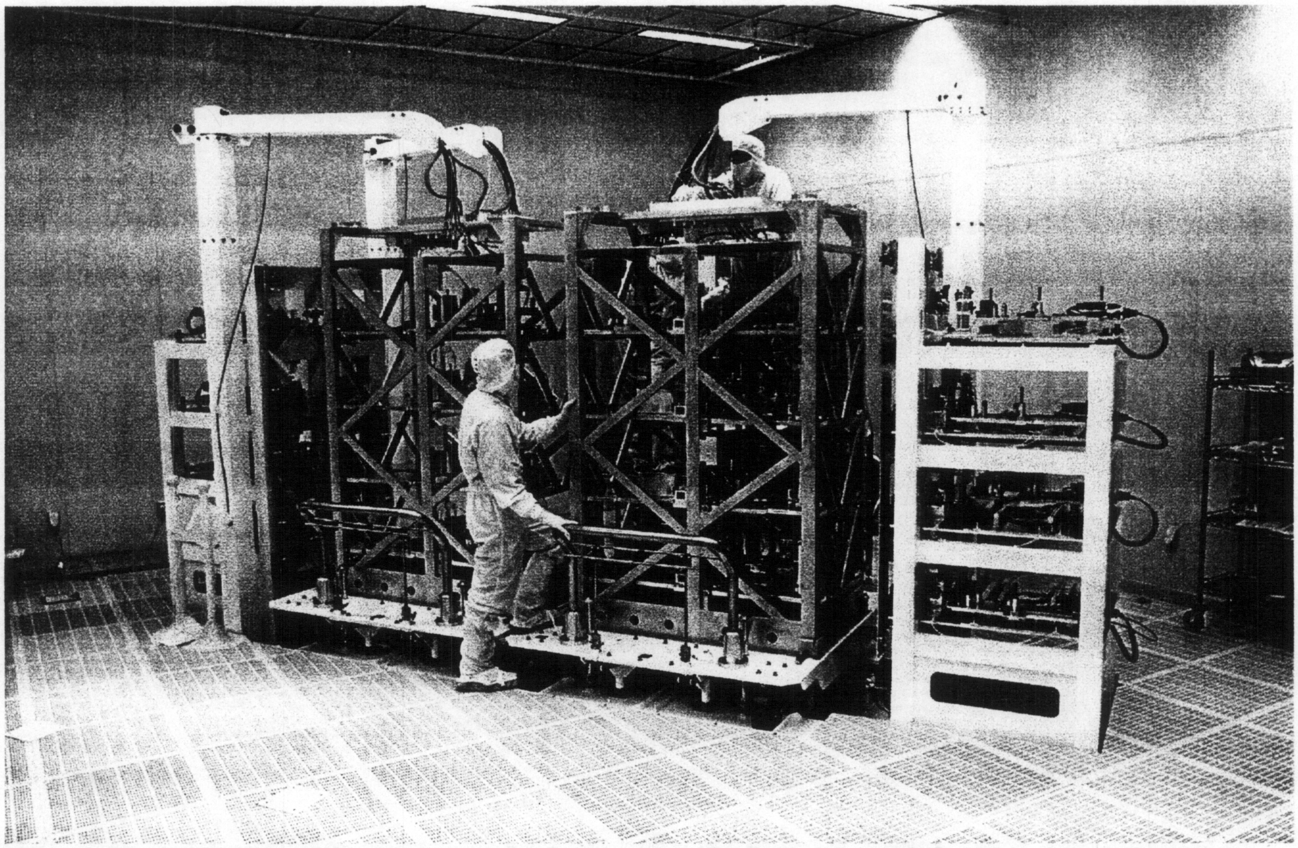

Figure 7. The Spatial Filter Tower LRUs undergo final testing in the Optics Assembly Building clean room prior to installation into the beam path.

3. Amplifiers

Upon exiting the Transport Spatial Filter, the laser pulse travels through the seven-slab-long Power Amplifier (PA) on its way to the multipass cavity. A second amplifier, the eleven-slab-long Main Amplifier (MA) is in the multipass cavity and sees four passes of the pulse, while the PA sees only two. Identical LRUs populate both amplifiers. The Slab LRU (Figure 8) holds four amplifier glass slabs at Brewster's angle relative to the beam. Each bundle of NIF holds 36 Slab LRUs with a NIF total of nearly 900. The Slab LRU must be very stiff and yet hold the fragile phosphate laser glass gently to avoid chipping or imparting stresses that could distort the large slabs. The mounting-induced distortion for each slab in the LRU must be less than 0.1 waves in order to meet the overall wavefront budget for the optical system. The LRU must also position the optic aperture to within 200 microns in the beam path enclosure.

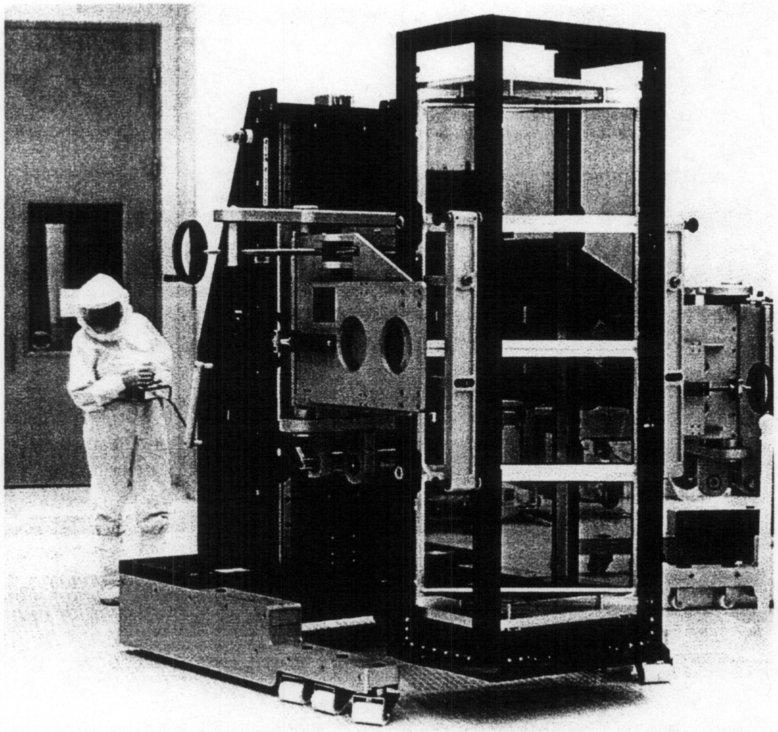

Figure 8. An assembled Slab LRU is moved from the assembly station in preparation for installation in the laser. The dark metal around the LRU is a protective frame for transport, while the light metal is the actual LRU.

The pump energy for the laser slabs comes from Flashlamp LRUs that are positioned on either side of the Slab LRU. There are 54 Flashlamp LRUs in each bundle for a total of ~1300 in NIF. The flashlamps are nearly two meters long and span the four-aperture height of the bundle. The Flashlamp LRUs hold either six or eight lamps, depending on their location, and contain specially shaped silver-coated reflectors to direct the pump light in a way that optimizes spatial gain uniformity in the amplifiers (see Figure 9). The silver coating is covered with a protective overcoat to prevent tarnishing that would degrade the amplifier performance over time.

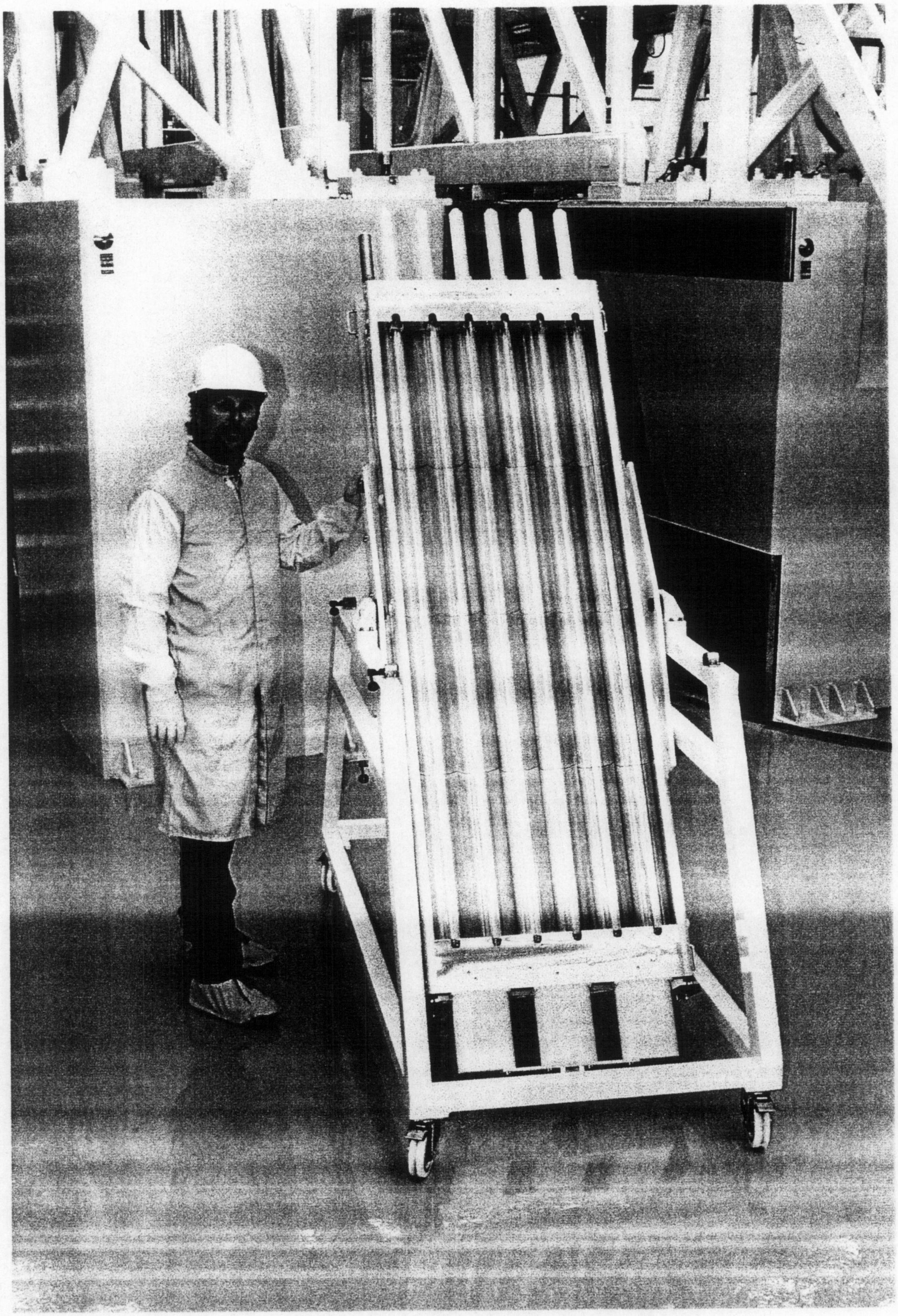

Figure 9. A flashlamp LRU resting on an assembly cart containing two-meter-long xenon flashlamps mounted near silver coated reflectors to aim the pump light onto the laser slabs with high efficiency.

The flashlamps are powered by a modular Power Conditioning System[1] (PCS) that stores energy in capacitors over about one minute and then discharges the energy into the flashlamps in about 500 microseconds. Each module of the PCS stores up to two megajoules of electrical energy and drives 40 flashlamps. Nine PCS modules are needed to drive each bundle. When the system is complete it will have up to 216 modules storing over 400 megajoules making the NIF PCS the world's largest capacitor bank. Figure 10 shows one of the PCS modules with the sides removed, revealing the 24 kV, 85 kJ capacitors, high-current switch and output coaxial cables. Each module has a dedicated charging power supply and control system. These units are assembled and fully tested off-site by an integrating contractor.

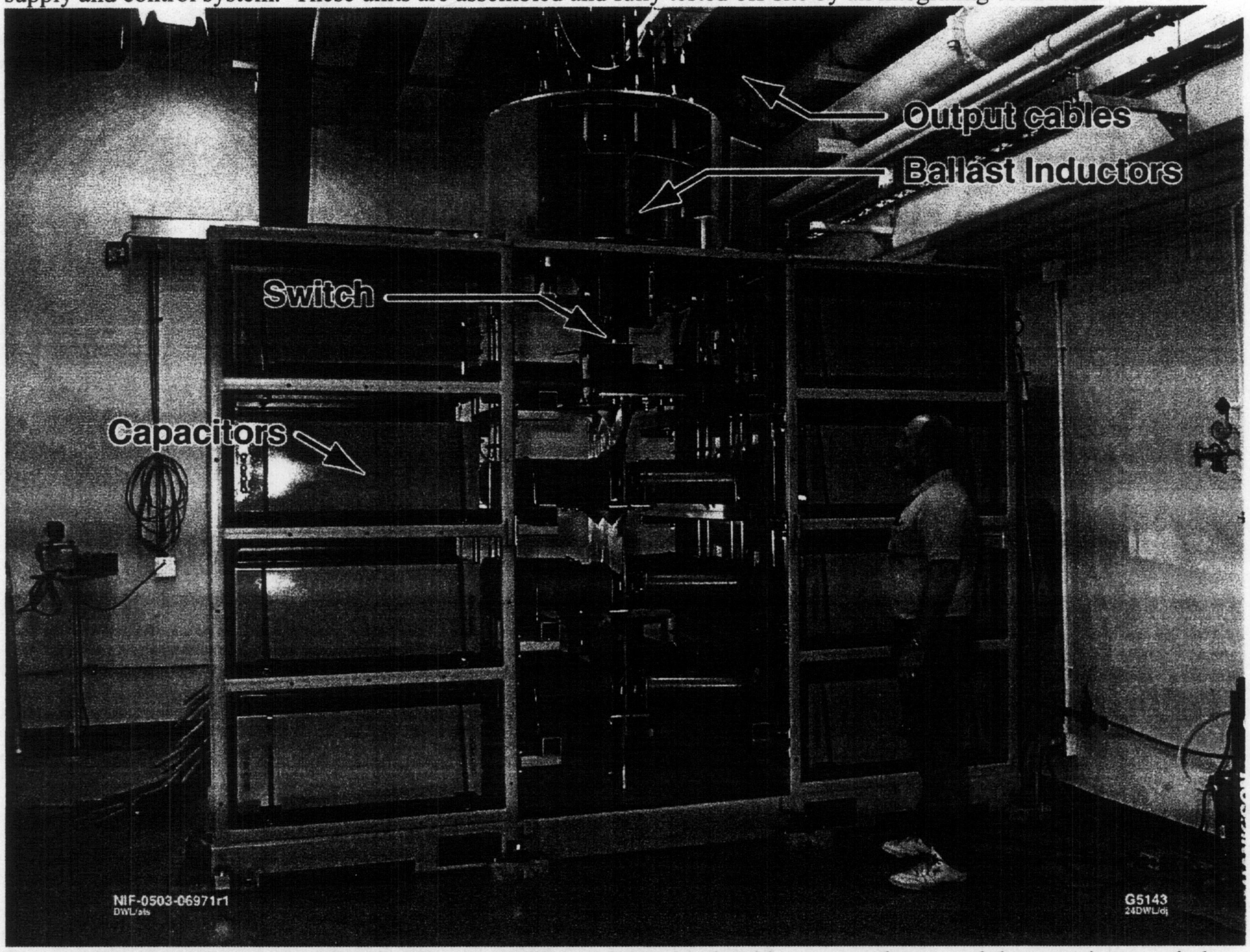

Figure 10. A 2 MJ Power Conditioning System (PCS) module with the sides removed to reveal the capacitors, switch and ballast inductors. Each output cable at the top of the module connects to two flashlamps in the laser amplifier.

4. Pockels Cell

The pulse enters the main laser cavity after leaving the Power Amplifier. The mirrors LM1 and LM2 form the ends of the main laser cavity (see figure 2). The Plasma Electrode Pockels Cell[2] (PEPC) combined with the cavity polarizer form an optical switch that allows the pulse to make two round trips in the cavity through the Main Amplifier. A full aperture Pockels Cell is a critical component of the NIF laser architecture. Traditional Pockels Cells are limited in aperture to a few centimeters since the circumferential electrodes typically employed require that the thickness of the crystal optic be on the same order as the diameter. In a PEPC, the electrodes are invisible (to the laser pulse) plasmas that are formed on either side of the crystal optic. The crystal is then "charged" by applying a voltage across the two plasma electrodes, effecting the desired rotation of the laser pulse polarization. The switch is turned "on" as soon as the pulse enters the cavity, trapping the laser pulse between LM1 and LM2. After the first round trip through the cavity, the switch is turned off, allowing the pulse to switch out of the cavity by reflecting off the polarizer. The PEPC LRU, shown in Figure 11, operates on a column of four beams within a bundle. The design of this LRU is complicated by the combination of high voltage, vacuum, plasma, space constraints and tight mechanical tolerances. The gas cell is anodized aluminum, and a one-centimeter thick glass frame with potassium dihydrogen phosphate (KDP) crystals is sandwiched between the two halves of the cell. The gas cell is mounted in a stainless steel frame that contains vacuum and process gas plenums, cable routes and kinematic mounting features. The switching efficiency across the 40 cm square aperture averages over 99.9%. The PEPC LRU is assembled and tested in the NIF OAB clean room prior to installation in the laser.

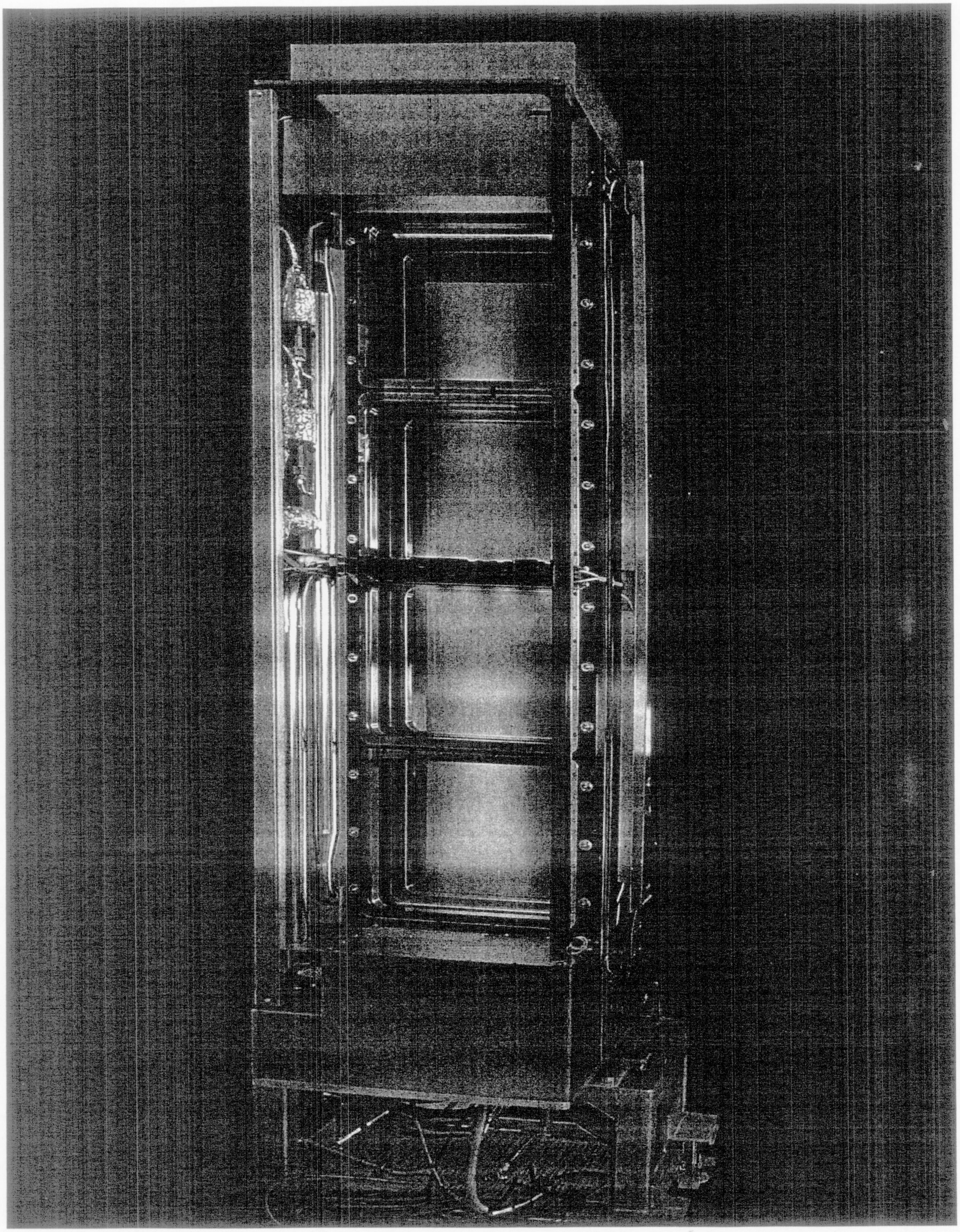

Figure 11. The Plasma Electrode Pockels Cell (PEPC) LRU assembled and ready to install in the laser.

5. Deformable Mirror

One end of the cavity, labeled LM1 in Figure 2, is a deformable mirror (DFM) used to improve the focusability of the laser beams[3]. This full aperture device has 39 actuators that deform the reflective surface of the mirror to compensate for fabrication and mounting imperfections in the rest of the NIF optical systems. The device also pre-corrects for wavefront errors that are produced when the flashlamps pump the laser slabs in the amplifiers. A Shack-Hartmann sensor in the one-micron laser output diagnostic package samples the wavefront error so that the proper actuator settings can be calculated. Figure 12 shows an individual DFM. Four of these assemblies are mounted in a column to assemble the LM1 LRU.

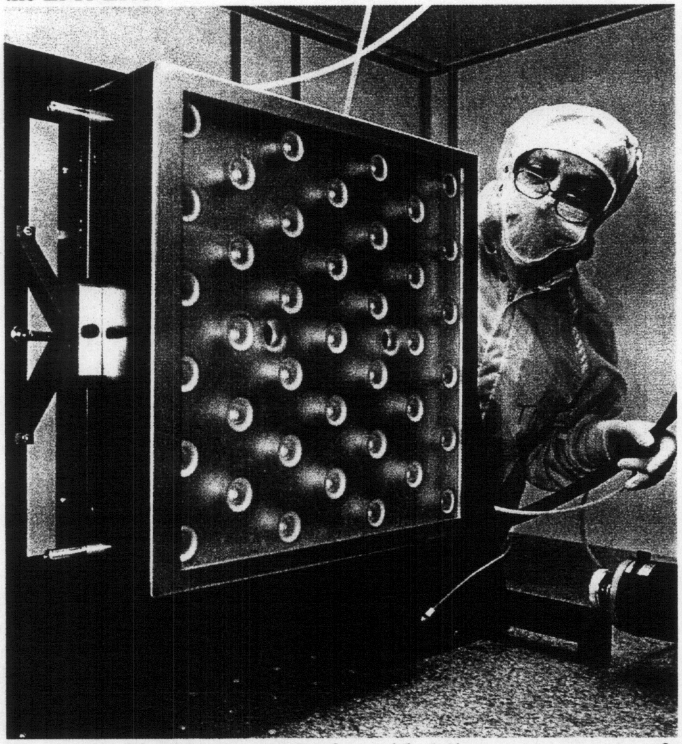

Figure 12. The 39 actuator Deformable Mirror corrects wavefront errors in the main laser to improve the focusability of the beam.

6. Beam Transport Mirrors

The laser pulse is switched out of the cavity after four passes through the main amplifier and proceeds back through the Power Amplifier and Transport Spatial Filter towards the Target Chamber. A series of Beam Transport mirrors direct the beams in groups of four (the top or bottom half of a bundle) around the target chamber to provide a symmetrical drive. A variety of LRU designs are required to perform this function in order as shown in Figure 13. These LRUs are typically made using welded sections of structural stainless steel tubing to provide stiffness and reduce vibration in the mounts. The mirrors are mounted using lugs that expand into holes bored in the glass mirror substrate and hold the optic with minimal surface distortion.

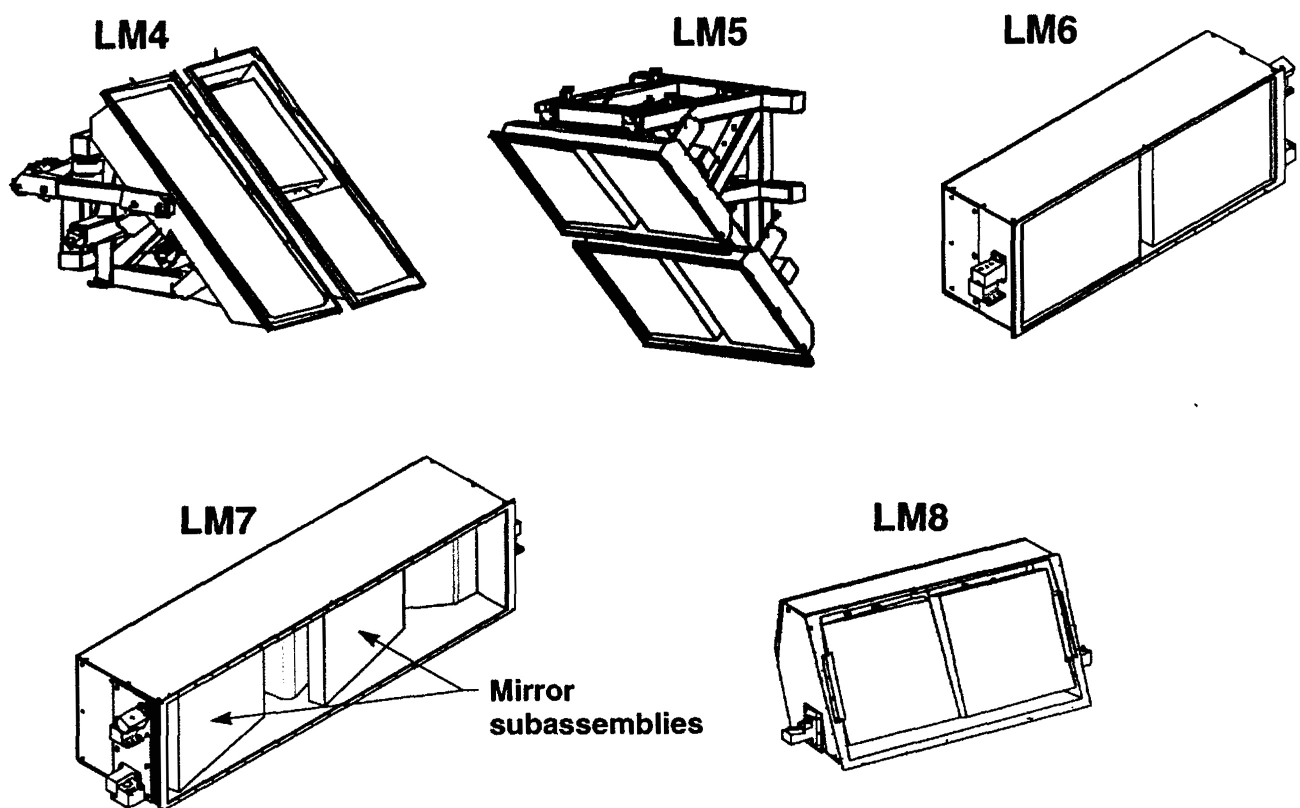

Figure 13. Several configurations of Transport Mirror LRUs are required to convert the planar symmetry of the main laser bundles to the spherical configuration of the target chamber.

7. Final Optics

The 1.06 micron laser beam is frequency tripled and focused to a spot in the center of the target chamber by the Final Optics Assembly (FOA). This four-beam assembly, shown in Figure 14, has several LRUs so that individual optics can be readily removed for inspection or replacement. In addition to the frequency converters and focusing lens, this assembly houses a beam sampling grating (BSG) that provides a sample of the laser drive pulse to a diagnostic package. At the output of this assembly are main debris shield (MDS) and disposable debris shield (DDS) that protect the FOA optics from shrapnel that is generated during target experiments. A target chamber vacuum window (TCVW) encloses the optics in the vacuum environment of the target chamber. This system of LRUs has very tight mechanical tolerances since the frequency conversion crystals must be oriented very precisely relative to the laser beam to assure efficient conversion of the light. In addition, the cleanliness requirements are even more stringent than the rest of the laser since damage from contamination is more likely in the presence of ultraviolet light.

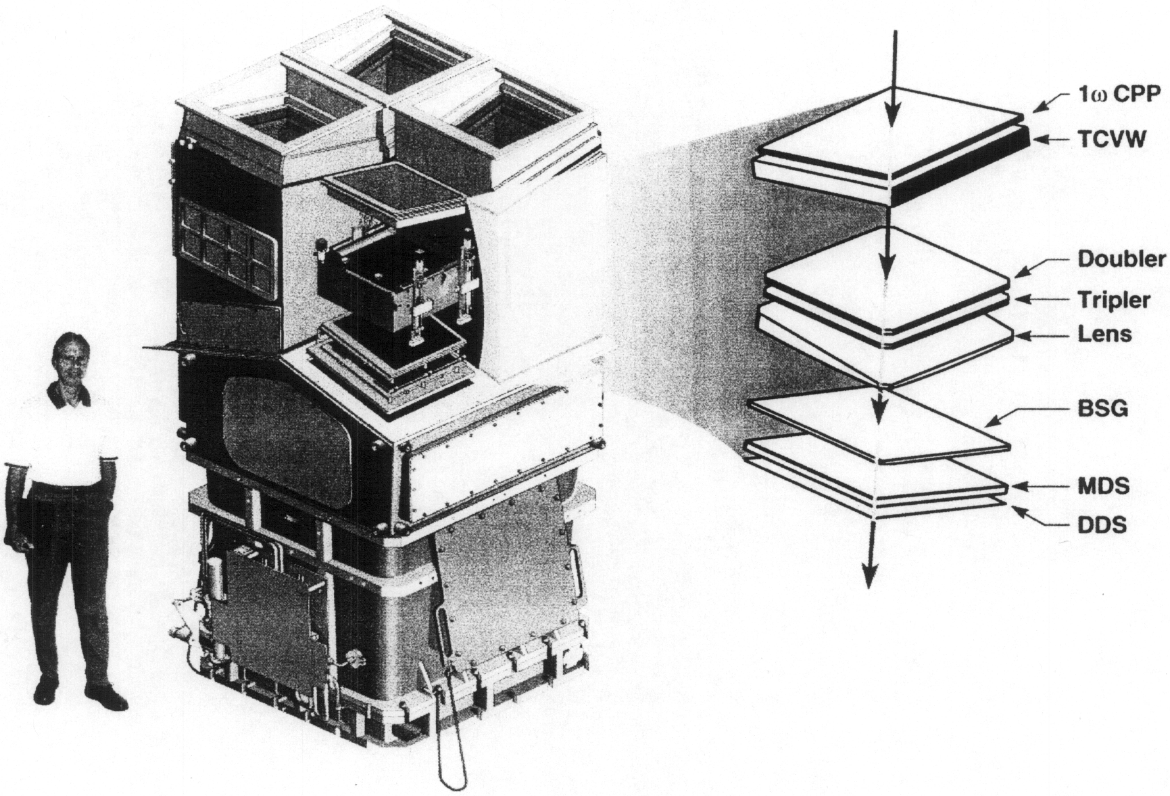

Figure 14. CAD representation of the Final Optics Assembly (FOA) indicating the various optics, including the continuous phase plate (1ω CPP), target chamber vacuum window (TCVW), frequency doubler and tripler crystals, focus lens, beam sampling grating (BSG), main debris shield (MDS) and disposable debris shield (DDS).

SUMMARY

When it is completed, the NIF will have over 4,000 LRUs holding the thousands of optics in the laser system. These complex optomechanical designs address the difficult optical, mechanical and cleanliness challenges of the NIF. Commissioning the first four beamlines of the NIF verified the performance of all of the LRUs. Production contracts are now in place to procure the remaining hardware on a schedule to complete the Project in 2008.

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